Modeling the effects of dissolved helium pressurant on a liquid hydrogen rocket propellant tank

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Abstract. A model was developed using NASA's Generalized Fluid System Simulation Program (GFSSP) for the self-pressurization of a liquid hydrogen propellant tank due to boil-off to determine the significance of mixture non-idealities. The GFSSP model compared the tank performance for the traditional model that assumes no helium pressurant dissolves into the liquid hydrogen propellant to an updated model that accounts for dissolved helium pressurant. Traditional NASA models have been unable to account for this dissolved helium due to a lack of fundamental property information. Recent measurements of parahydrogen-helium mixtures enabled the development of the first multi-phase Equation Of State (EOS) for parahydrogen-helium mixtures. The self-pressurization GFSSP model was run assuming that the liquid propellant was pure liquid hydrogen and assuming helium dissolved into the liquid utilizing the new helium-hydrogen EOS. The analysis shows that having dissolved helium in the propellant does not have a significant effect on the tank pressurization rate for typical tank conditions (-423 °F and 30 psia).

1. Introduction

Helium is typically used to pressurize liquid hydrogen propellant tanks to maintain tank pressure and reduce boil-off. This causes helium gas to dissolve into the liquid hydrogen creating a cryogenic mixture with thermodynamic properties that vary from those of pure liquid hydrogen. This can lead to inefficiencies in fuel storage and instabilities in fluid flow. This has yet to be a major concern because mission durations where liquid hydrogen is the propellant are typically on the order of minutes to a few hours. A cryogenic upper stage has yet to be fired outside of the Earth's orbit. As NASA plans for longer missions to Mars and beyond, small inefficiencies in propellant storage become significant.

Traditional NASA models have previously been unable to account for the effects of dissolved helium due to a lack of fundamental property measurements necessary for a mixture Equation Of State (EOS). This work builds off of the Pressure-Density-Temperature-Composition (PρT-x) measurements of helium-hydrogen mixtures that were used to develop the first multi-phase EOS for helium-hydrogen mixtures [1]. This new EOS was incorporated into NASA's Generalized Fluid System Simulation Program (GFSSP) software to determine the significance of dissolved helium on the bulk tank performance. A simple self-pressurization of a liquid hydrogen tank was used to compare the effects of dissolved helium on the tank characteristics.

2. Self-Pressurization Model for a Liquid Hydrogen Tank

The self-pressurization model used in this work was based on NASA's GFSSP Example 29 "Self-Pressurization of a Cryogenic Propellant Tank Due to Boil-off" [2]. Example 29 simulates the self-

pressurization of a ground-based liquid hydrogen tank that was conducted under the Multi-Purpose Hydrogen Test Bed (MHTB) program. The original problem investigates a Thermodynamic Vent System (TVS). The TVS portion of Example 29 is beyond the scope of this work and was removed from the original model. Only the self-pressurization portion of the tank model was investigated to determine the effects of dissolved helium on the tank performance. A detailed discussion of the tank and the thermodynamic relations used to solve the system can be found in the GFSSP Supplemental Materials for version 701 [2]. A brief overview of the tank and thermodynamic relations used is presented. English units are used in this work for consistency and validation with the original GFSSP example as this is the unit system typically used by NASA.

   This example models a ground-based liquid hydrogen storage tank that is subject to Earth's gravity. The 5083 aluminum tank is cylindrical with a height and diameter of 10 feet. The ends of the tank are elliptical domes. The internal volume is 639 ft^3. The model was initially validated by solving for the self-pressurization rate of the tank for a pure hydrogen tank and comparing the results to the original model in Example 29. Once the model was validated, the foam insulation and multi-layer insulation (MLI) was eliminated from the original model in Example 29 to decrease computational time. The radiation load on the tank walls was computed from the original model and then assumed constant over the course of the run. Since the purpose of this work is to compare the tank performance assuming the liquid propellant is pure hydrogen and then accounting for dissolved helium in the liquid, this assumption will not affect the overall findings and conclusions. The liquid-vapor interface was modeled as a thin film of zero volume. Figure 1 shows the GFSSP model of the settled MHTB tank for a 50% fill level.
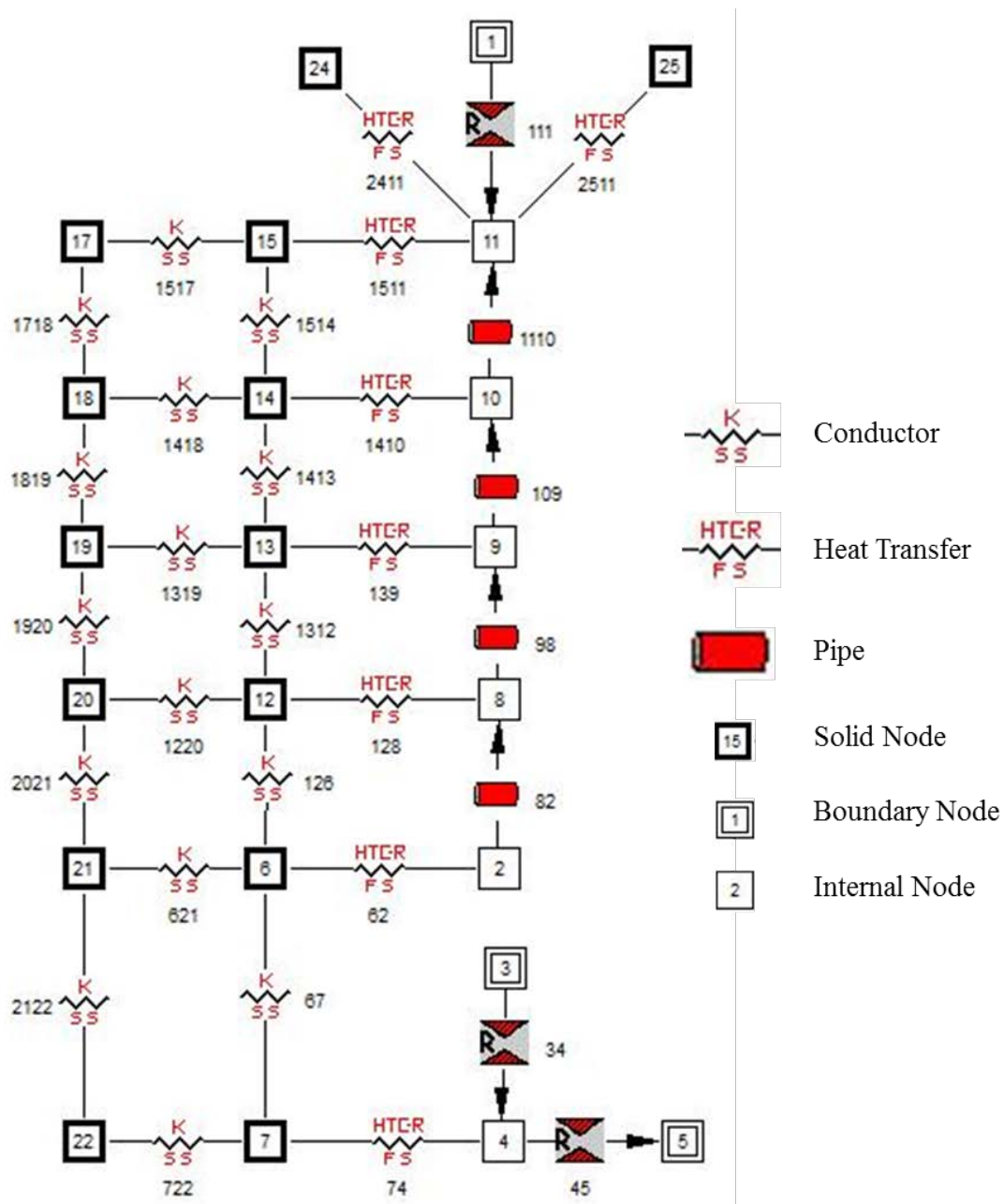
Figure 1. GFSSP nodal network for the self-pressurization of a liquid hydrogen propellant tank model.

The model was kept identical to Example 29 with the exception of the MLI to compare results to the original model. The key components of the nodal network shown in Figure 1 are that Node 4 represents the liquid while nodes 2, 8, 9, 10, and 11 represent the ullage at fill levels of 54 %, 65 %, 80 %, 92 %, and 98 % respectively. The nodes on the left-hand side, similar to nodes 7 and 22, are solid nodes representing the tank wall.

Node 3 acts as a pseudo-node to separate the liquid from the ullage. The boundary between the liquid and ullage is modeled as a thin film with no mass or volume. The interface allows mass and heat to exchange between the ullage and liquid volumes as the liquid evaporates. Figure 2 shows the terms considered at the interface.
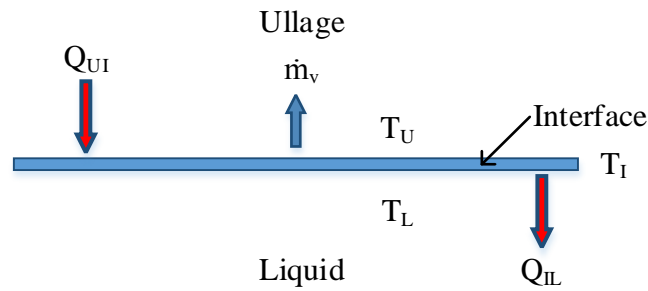
Figure 2. Diagram of heat and mass transfer across the liquid-vapor interface.

The ullage contains superheated vapor and pressurant at temperature, T_U. The interface temperature, T_I, is determined by the saturation temperature of the liquid at the ullage pressure. T_L is the temperature of the liquid and is assumed to be uniform. The evaporative mass is determined using

$$\dot{m}=\frac{Q_{UI}-Q_{IL}}{h_{fg}} \tag{1}$$

where Q_{UI} is the heat transfer from the ullage into the interface, Q_{IL} is the heat transfer from the interface into the liquid, and h_{fg} is the enthalpy of vaporization. The heat transfer from the ullage to the interface is expressed as

$$Q_{UI}=h_{UI}A\left(T_U-T_I\right) \tag{2}$$

where h_{UI} is the heat transfer coefficient between the ullage and the interface and A is the surface area of the interface. The heat transfer from the interface to the liquid is expressed as

$$Q_{IL}=h_{IL}A\left(T_I-T_L\right) \tag{3}$$

where h_{IL} is the heat transfer coefficient between the interface and the liquid. The heat transfer coefficient was computed from natural convection correlations, also known as free convection, for the lower surface of a hot plate or upper surface of a cold plate outlined by Incropera and DeWitt [3]. The heat transfer coefficient was kept consistent with the original model in Example 29 and is expressed as

$$h_{UI}=K_H C\frac{k_f}{L_s}Ra^n=h_{IL} \tag{4}$$

Where K_H is a correction factor equal to 0.5, C is an empirical factor from the Nusselt number correlation and is equal to 0.27, k_f is the thermal conductivity of the fluid, L_s is the characteristic length, Ra is the Rayleigh number, and n is equal to 0.25. In order for the model to solve, the heat transfer coefficients had to be set equal to each other based on the thermodynamic properties of the ullage. This is consistent with Example 29 in the GFSSP Supplemental Materials version 701. The heat transfer between the bulk fluid and the tank wall was calculated using natural convection correlations for a vertical plate.

In order to determine the effects of dissolved helium pressurant, the model was modified to incorporate helium pressurant in the ullage. The liquid was initially assumed to be pure parahydrogen at -423 °F which corresponds to a saturation pressure of 15.14 psia [4]. Thus the partial pressure of parahydrogen in the tank was assumed to be 15.14 psia and the remainder was attributed to the helium pressurant. For this work the tank pressure was set to a typical operating pressure of 30 psia. The composition of helium and parahydrogen within the ullage was determined using Dalton's Law of partial pressures. The ullage was assumed to be an ideal binary mixture. The model simulation time was 10 hours in order to observe the bulk tank properties.

The model was then modified to incorporate dissolve gaseous helium into the liquid parahydrogen in order to compare the differences. The amount of helium that dissolves in liquid hydrogen was calculated from the empirical solubility model of Zimmerli et al. which depends on the total tank pressure and the temperature of the liquid [5]. For the assumed liquid temperature of -423 ˚F and total tank pressure of 30 psia, the solubility model predicts that 0.17 mole % helium will dissolve into the

liquid propellant. Thus, thermodynamic property tables were created for a mixture of 99.83 mole % parahydrogen – 0.17 mole % helium using the mixture equation of state for parahydrogen-helium developed by Blackham et al [1]. The property tables were incorporated into GFSSP to supply the liquid properties. The ullage properties were the same as for the pure liquid hydrogen case. For modeling purposes, the liquid was treated as a pure fluid. The model was solved using the liquid properties corresponding to 99.83 mole % parahydrogen – 0.17 mole % helium.

3. Modeling Results

The most critical tank performance metric is the self-pressurization rate as it determines how often the tank must be vented and how much propellant will be lost. This model investigated the pressurization rate with the initial assumption that no helium dissolves in the propellant and then accounting for 0.17 mole % dissolved helium in the liquid parahydrogen propellant. Both models assume helium pressurant in the ullage and an initial tank pressure of 30 psia. The results are shown in Figure 3.
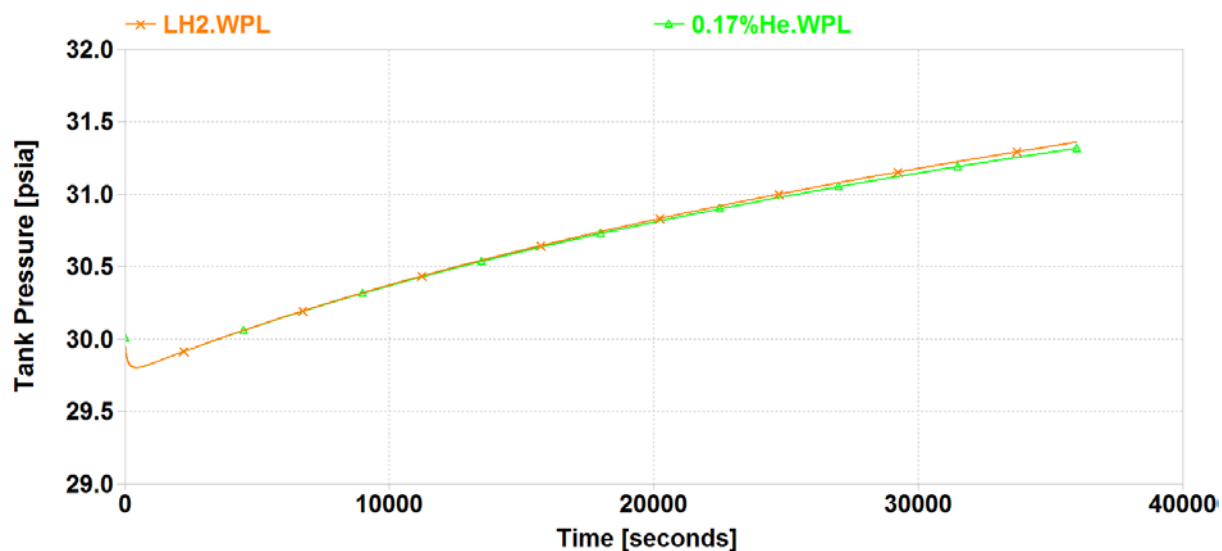

Figure 3. Comparison of the self-pressurization rate of a liquid hydrogen propellant tank assuming pure liquid hydrogen propellant (orange x's) and 0.17 mol % dissolved helium in the liquid (green triangles).

Figure 3 shows there is no significant difference in the predicted self-pressurization rate of a 30 psia propellant tank when accounting for the dissolved helium pressurant over a 10 hour mission. Another tank characteristic that is of interest is the temperature of the propellant as it will affect the density of the liquid and thus the mass flowrate out of the propellant tank. Figure 4 shows the temperature of the liquid over a 10 hour mission for pure parahydrogen propellant and accounting for 0.17 mole % dissolved helium in the propellant.
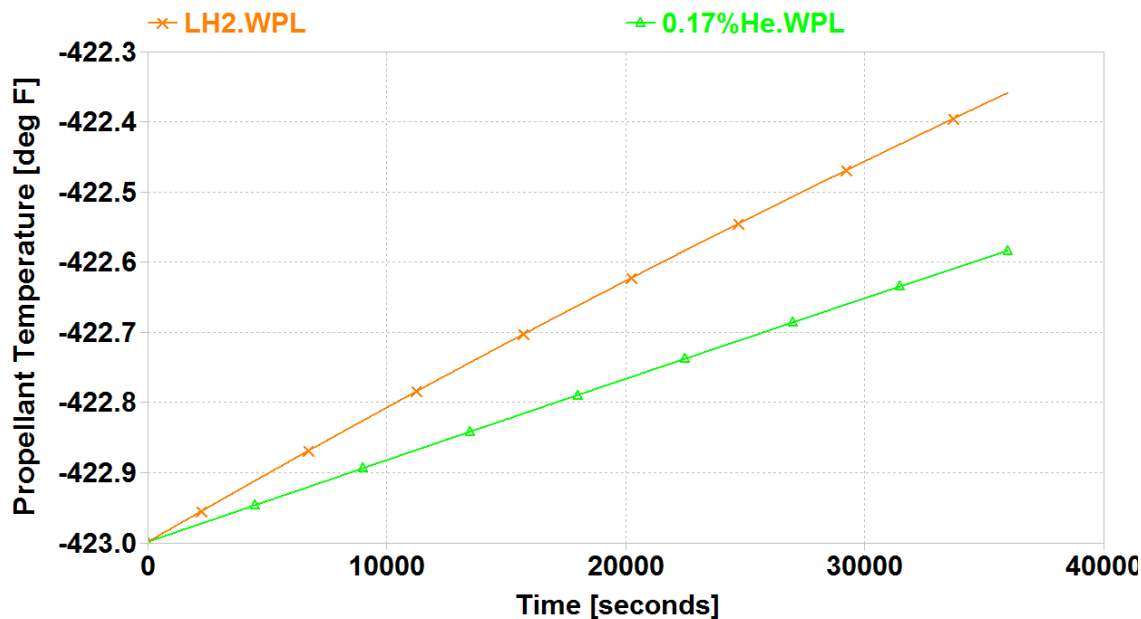
Figure 4. Comparison of the propellant temperature assuming pure liquid hydrogen propellant (orange x's) and 0.17 mole % dissolved helium (green triangles).

The GFSSP model predicted a $0.2\,°F$ difference in the propellant temperature over the course of the 10 hour mission when accounting for dissolved helium pressurant. Figure 4 shows that dissolved helium slightly decreases the rate at which the propellant temperature rises.

4. Conclusions and Recommendations for Future Research

The self-pressurization of a liquid hydrogen propellant tank was modeled using GFSSP to determine the significance of dissolved helium pressurant in the liquid propellant on the tank performance. The model revealed that dissolved helium pressurant does not have a significant effect on the tank pressurization rate. The model showed a slight decrease in the rise of the propellant temperature. It is important to note that the solubility model used in this work is based on steady state conditions and does not take into account the transport properties of helium in liquid hydrogen [5]. Experiments conducted on NASA's Evolvable Cryogenics (eCryo) Engineering Design Unit (EDU) tank and the PρT-x measurements on helium-hydrogen mixtures revealed liquid hydrogen pressurized with helium injected directly into the liquid requires considerably more time to reach steady state than helium injected into the ullage. This phenomenon has been discussed in detail by Richardson [6]. The rate at which helium dissolves in or degasses from liquid hydrogen has not been studied. This will bias the amount of helium in the liquid propellant as the mixture slowly achieves chemical equilibrium.

While developing the self-pressurization model, it was discovered that a large uncertainty in the pressurization rate was due to the uncertainty in the heat transfer coefficients. The heat transfer coefficients that were used in this model are based on generic natural convection correlations. These correlations contain constants that were determined based on traditional fluids like air. The heat transfer coefficients for liquid hydrogen and saturated hydrogen vapor are not well characterized. Additional heat transfer coefficient measurements on liquid hydrogen and liquid hydrogen with dissolved helium would improve model accuracies.

If helium continues to be used as a pressurant for liquid hydrogen rocket propellant for longer duration missions such as fueling depots and traveling to the Mars, the effects of dissolved helium in liquid hydrogen need to be investigated further and better understood. Experimental measurements of the transport properties and heat transfer coefficients should be conducted to increase the accuracy of predictive models.

References

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